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Application of Adaptive Dead-Beat Controller in Drying Process

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Abstract

In the article a temperature control is dealt in drying machines during a manufacturing process of printed circuits boards. A problem occurs if the temperature is not complied during a drying process of a solder mask and a service printing. It involves to depreciation of the printed circuit board, especially if the surface mount devices are used. An adaptive polynomial controller was designed to improve the temperature control. The controller is constructed by dead-beat method and it is implemented into 8-bit microcontroller, which has supervision of control process of whole drying system.
The controller is based on a recursive identification algorithm, which identifies the dryer system. That identification proceeds continuously during the printed circuits boards drying process. Parameters of controller are recalculated in each period on the basis of data obtained by identification.

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Keywords: controller; drying process; microcontroller; printed circuit board; recursive identification

1. Introduction

Nowadays a fast manufacture of prototype printed circuit boards are demanded especially in design of electronics devices such as digital circuit parts, controlling structures, radiofrequency components and analogue measuring devices. These devices are often tested and changes are made in a lot of case, especially to achievement of desired parameters. Therefore, the printed circuit boards are often changed and redesigned. In these cases it is necessary to product fast and cheap the prototype boards in a small amount. These boards are manufactured in several classes, which are usually marked from III to IX, where the III class is the lowest level for the simple boards and the IX class is the highest level for the six-layered board which are usually produced by photolithography [1].

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Almost the all boards are covered by a soldering mask and a service printing and also they can include other layers (HAL, golden plating and protective varnish).

The solder mask facilitates a soldering process, and prevents to shortcuts (bridges) between leads or a soldering paste spilling in a reflow process. A lot of parts cannot be generally soldered without the mask, or it can be done with problems. For example, surface mount devices in packages like LQFP, QFN or BGA have got 0.5mm pitch and they demand the solder mask. Service printing is not important part for proper electronic functions, but it aids to manual parts mounting, to identify and repair of the boards.

The two-component polymer photoimageable masks were developed, because they must resist to high temperature (from 200°C to 350°C) during soldering processes (manual, wave soldering, infrared heating and reflow soldering) and because they should resist to chemical cleaning. These masks require drying after a coating on the printed circuit board and a hardening as a finishing step [2]. The drying temperature is usually recommended about 85°C [2]; however, it depends on a form of drying (horizontally, vertically, single or multiple boards) and an air flow (circulation, intake of fresh air and outlet of fumes). If the temperature is overshooted, the mask cannot be usually removed; on the other hand, if the temperature does not reach the appropriate value, the mask does not adhere on the board and flakes off. This case can be seen on the Fig. 1.

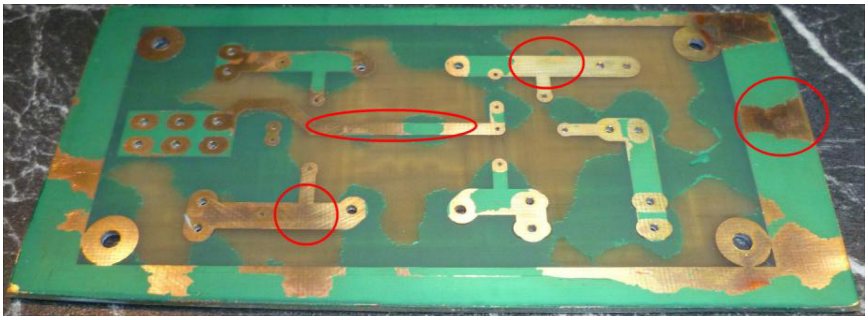

Fig. 1. Printed circuit board with missing solder mask (examples are circled).

An adaptive polynomial controller [3] for the temperature control in the dryer is introduced in this work. The adaptive controller replaced the insufficient two-state bimetal controller, which oscillated approx. 15°C about the set temperature, therefore the mask was often overheated or the temperature often does not achieved the set value. The adaptive controller is designed to use in a lot of kind of dryer, not only in the dryer where it was tested. The algorithm is implemented on a basis of an 8-bit HCS08 microcontroller. At the end of article a proper results of the adaptive controller are shown.

2. Least-squares identification method

A recursive least-squares identification method [3-6], provides systems identification for a controller parameters calculation. This method was selected due to it is need only a small amount memory for data, which is very important if the identification algorithm is implemented in the microcontroller. Two last samples of dryer temperature and two last values of controller output are enough data which are needed for identification. A second-order equation (1) describing the drying system can be deduced on knowledge of temperature curves.

$$G\left(z^{-1}\right)=\frac{b_1 z^{-1}+b_2 z^{-2}}{1+a_1 z^{-1}+a_2 z^{-2}} \tag{1}$$

An implicit least-squares identification method is described by (2)

$$\hat{\mathbf{\Theta}}=\left(\mathbf{F}^T\mathbf{F}\right)^{-1}\mathbf{F}^T\mathbf{y} \tag{2}$$

This equation can be rewritten for $k-1$ measurements into form

$$\hat{\mathbf{\Theta}}(k-1)=\left(\mathbf{F}_{k-1}{}^{T}\mathbf{F}_{k-1}\right)^{-1}\mathbf{F}_{k-1}{}^{T}\mathbf{y}(k-1) \tag{3}$$

where:

$$\mathbf{y}^{T}(k-1)=\left[y(1)\quad y(2)\quad \ldots \quad y(k-1)\right] \tag{4}$$

is a vector of output variables in the interval $(1, k-1)$, and

$$\hat{\mathbf{\Theta}}(k-1)=\left[\hat{\theta}_{1}(k-1)\quad \hat{\theta}_{2}(k-1)\quad \ldots \quad \hat{\theta}_{r}(k-1)\right] \tag{5}$$

is vector of optimal estimates of parameter values of transfer function. A matrix

$$\mathbf{F}_{k-1}=\begin{bmatrix} f_1(1) & f_2(1) & \ldots & f_r(1) \\ f_1(2) & f_2(2) & \ldots & f_r(2) \\ \vdots & \vdots & \vdots & \vdots \\ f_1(k-1) & f_2(k-1) & \ldots & f_r(k-1) \end{bmatrix} \tag{6}$$

is modified matrix $\mathbf{F}$ for $(k-1)$ measurements. If k-measurement is done and

$$\mathbf{y}(k)=\begin{bmatrix} y(k-1) \\ y(k) \end{bmatrix} \tag{7}$$

is described, the matrix (8)

$$\mathbf{F}_{k}=\begin{bmatrix} \mathbf{F}_{k-1} \\ \mathbf{\Phi}^{T}(k) \end{bmatrix} \tag{8}$$

can be written, where

$$\mathbf{\Phi}^{T}(k)=\left[f_1(k)\quad f_2(k)\quad \ldots \quad f_r(k)\right] \tag{9}$$

The vector (10) can be written for k-measured variable

$$y(k)=\mathbf{\Theta}^{T}\mathbf{\Phi}(k)+e(k) \tag{10}$$

where $\mathbf{\Theta}^{T}$ is defined as:

$$\mathbf{\Theta}^{T}=\left[\theta_1\quad \theta_2\quad \ldots \quad \theta_r\right] \tag{11}$$

A covariance matrix $\mathbf{C}(k)$ can be defined as

$$\mathbf{C}(k)=\left[\mathbf{F}_{k-1}^{T}\mathbf{F}_{k-1}+\mathbf{\Phi}(k)\mathbf{\Phi}^{T}(k)\right]^{-1} \tag{12}$$

And it can be written as

$$\mathbf{C}(k)=\left[\mathbf{C}^{-1}(k-1)+\mathbf{\Phi}(k)\mathbf{\Phi}^{T}(k)\right]^{-1} \tag{13}$$

A general recursive algorithm can be written as

$$\hat{\mathbf{\Theta}}(k)=\hat{\mathbf{\Theta}}(k-1)+\mathbf{K}(k)\left[y(k)-\hat{\mathbf{\Theta}}^{T}(k-1)\mathbf{\Phi}(k)\right] \tag{14}$$

where $\mathbf{K}(k)$ is time changing vector of gain and can be written as

$$\mathbf{K}(k)=\frac{\mathbf{C}(k-1)\mathbf{\Phi}(k)}{1+\mathbf{\Phi}^{T}(k)\mathbf{C}(k-1)\mathbf{\Phi}(k)} \tag{15}$$

The recursive equation for covariance matrix is

$$\mathbf{C}(k)=\mathbf{C}(k-1)-\mathbf{C}(k-1)\frac{\mathbf{\Phi}(k)\mathbf{\Phi}^{T}(k)\mathbf{C}(k-1)}{1+\mathbf{\Phi}^{T}(k)\mathbf{C}(k-1)\mathbf{\Phi}(k)} \tag{16}$$

The vector of parameters $\mathbf{\Theta}^{T}(k)$ and vector of measurement data $\mathbf{\Phi}^{T}(k)$ can be written for second order transfer function as:

$$\mathbf{\Theta}^{T}(k)=\left[a_1 \quad a_2 \quad b_1 \quad b_2\right] \tag{17}$$

$$\mathbf{\Phi}^{T}(k)=\left[-y(k-1) \quad -y(k-2) \quad u(k-1) \quad u(k-2)\right] \tag{18}$$

3. Adaptive controller

The dead-beat controller was chosen for the implementation, because it also ensures the achievement of regulated variable also among two periods, not only when the period just occurs.
This controller ensures the stability of regulated variable also among measurement periods [3, 7, 8]. The closed loop can be described by equations (19) and (20):

$$Y\left(z^{-1}\right)=\frac{B\left(z^{-1}\right)}{A\left(z^{-1}\right)}U\left(z^{-1}\right) \tag{19}$$

$$U\left(z^{-1}\right)=\frac{R\left(z^{-1}\right)}{P\left(z^{-1}\right)}W\left(z^{-1}\right)-\frac{Q\left(z^{-1}\right)}{P\left(z^{-1}\right)}Y\left(z^{-1}\right) \tag{20}$$

where $U\left(z^{-1}\right)$, $Y\left(z^{-1}\right)$ and $W\left(z^{-1}\right)$ are polynomials of corresponding signals. The Controller output $U\left(z^{-1}\right)$ and the regulated signal $Y\left(z^{-1}\right)$ can be written after the modification of (19) and (20):

$$Y\left(z^{-1}\right)=\frac{B\left(z^{-1}\right)R\left(z^{-1}\right)}{A\left(z^{-1}\right)P\left(z^{-1}\right)+B\left(z^{-1}\right)Q\left(z^{-1}\right)}W\left(z^{-1}\right) \tag{21}$$

$$U\left(z^{-1}\right)=\frac{A\left(z^{-1}\right)R\left(z^{-1}\right)}{A\left(z^{-1}\right)P\left(z^{-1}\right)+B\left(z^{-1}\right)Q\left(z^{-1}\right)}W\left(z^{-1}\right) \tag{22}$$

and control error $E\left(z^{-1}\right)$

$$E\left(z^{-1}\right)=\left[1-\frac{B\left(z^{-1}\right)R\left(z^{-1}\right)}{A\left(z^{-1}\right)P\left(z^{-1}\right)+B\left(z^{-1}\right)Q\left(z^{-1}\right)}\right]W\left(z^{-1}\right) \tag{23}$$

If the control error is required to be zero in the finite steps, the polynomial $E\left(z^{-1}\right)$ has to be simple. This condition is satisfied if the polynomial equation

$$A\left(z^{-1}\right)P\left(z^{-1}\right)+B\left(z^{-1}\right)Q\left(z^{-1}\right)=1. \tag{24}$$

It has solution for

$$\begin{aligned}\partial P\left(z^{-1}\right)&=\partial B\left(z^{-1}\right)-1\\ \partial Q\left(z^{-1}\right)&=\partial A\left(z^{-1}\right)-1\end{aligned}. \tag{25}$$

The equation (24) is also condition for stability of the closed loop system. The equation (23) can be simplified by using (24)

$$E\left(z^{-1}\right)=\left[1-B\left(z^{-1}\right)R\left(z^{-1}\right)\right]W\left(z^{-1}\right), \tag{27}$$

and $W\left(z^{-1}\right)$, that describes time continuous progress of the control value, can be written as

$$W\left(z^{-1}\right)=\frac{N_w\left(z^{-1}\right)}{D_w\left(z^{-1}\right)} \tag{28}$$

A simplification of (27) is possible if

$$S\left(z^{-1}\right)=\frac{1-B\left(z^{-1}\right)R\left(z^{-1}\right)}{D_w\left(z^{-1}\right)}, \tag{29}$$

that can be rewritten into equation

$$D_w\left(z^{-1}\right)S\left(z^{-1}\right)+B\left(z^{-1}\right)R\left(z^{-1}\right)=1 \tag{30}$$

with solution

$$\begin{aligned}\partial R\left(z^{-1}\right)&=\partial D_w\left(z^{-1}\right)-1\\ \partial S\left(z^{-1}\right)&=\partial B\left(z^{-1}\right)-1\end{aligned}. \tag{31}$$

The polynomial $S\left(z^{-1}\right)$ is not necessary to calculate during a control process, but it can be used for the error calculation. The equations (25) and (31) can be solved by the indefinite coefficient method. The algorithm is used for a $W\left(z^{-1}\right)$ tracking that must be known in advance. Practically steps are used, which can be written as

$$W\left(z^{-1}\right)=\frac{N_w\left(z^{-1}\right)}{D_w\left(z^{-1}\right)}=\frac{w_1}{1-z^{-1}}\ . \tag{32}$$

The control step is considered as $w_1 = 1$ for next simplification. Next, the equation (30) can be written as

$$\left(1-z^{-1}\right)S\left(z^{-1}\right)+B\left(z^{-1}\right)R\left(z^{-1}\right)=1\ . \tag{33}$$

According to (31), the polynomial $R\left(z^{-1}\right)$ has zero degree and as a solution of (33) is

$$r_0=\frac{1}{b_1+b_2+\ldots+b_n}\ . \tag{34}$$

A solution of Diophantine equation (24) for the second order system (1) leads to a system of matrixes

$$\begin{bmatrix} b_1 & 0 & 1 \\ b_2 & b_1 & a_1 \\ 0 & b_2 & a_2 \end{bmatrix}\begin{bmatrix} q_0 \\ q_1 \\ p_1 \end{bmatrix}=\begin{bmatrix} -a_1 \\ -a_2 \\ 0 \end{bmatrix} \tag{35}$$

The controller output can be described by

$$u(k)=r_0w(k)-q_0y(k)-q_1y(k-1)-p_1u(k-1) \tag{36}$$

where r_0 is calculated by

$$r_0=\frac{1}{b_1+b_2} \tag{37}$$

4. Description of the controller hardware

The implementation of the adaptive controller is based on the 8-bit microcontroller [12], which is the main controlling part that provides communication with an AD converter, displays and a power board. The microcontroller was selected from a HCS08 family which is manufactured by Freescale Semiconductor. That device is intended for the automotive use and general purposes [9]. It has 60kb flash memory and 4kb of RAM. Its core runs on 40MHz and an internal bus is clocked at 20MHz. Other peripheries (internal 12-bit ADC, communication peripheries) are also connected to this bus. A 16-bit external AD converter was used to the temperature measurement, because it provides the internal programmable gain amplifier [10], which can be dynamically changed to get a high resolution of temperature.

Two Pt1000 sensors are used in the dryer, because it gives superior information about a thermal profile. The highest temperature are always selected and used for next processing in the controller.

The hardware is designed on several small printed circuit boards due to the application in existing dryer without electronic or with low amount of space. This solution facilitates installation of the main board (Fig. 2), boards with displays and buttons and a power board; however, the installation can be executed at remote place, because sensor can be connected by 4-wire cable. This type of connection improves accuracy and eliminates resistivity of wires.

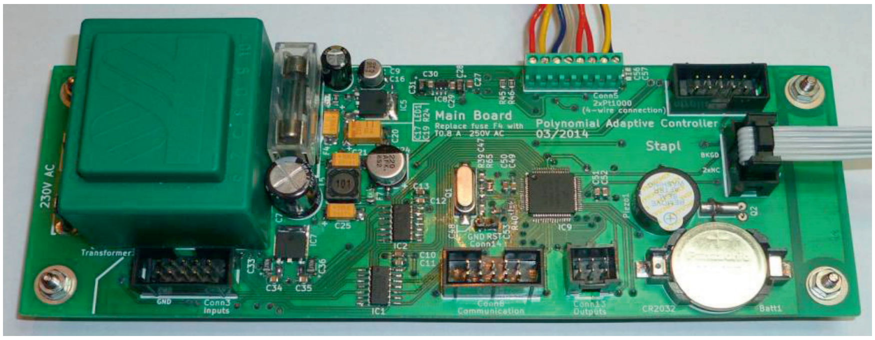

Fig. 2. Main controller board (dimensions 175x60mm).

5. Verification

The adaptive controller was verified at the real device. The dryer is capable to dry the board up to 20x30 centimeters, includes 1600W electrical heater and the dryer was insulated by heat resistant wool with thermal conductivity α=0.05 $Wm^{-1}K^{-1}$. The first tests were done at 35°C ambient temperature without the air flow. The parameters identification was proceeded and the system described by (38) was got for Fig. 3 (a) and the system described by (39) was got for Fig. 3 (b).

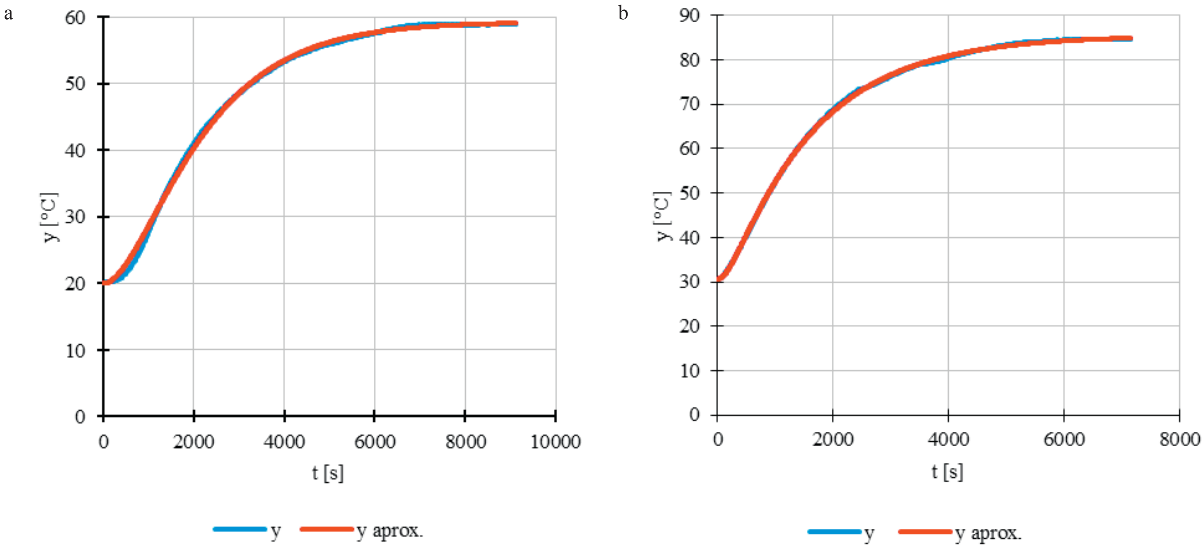

Fig. 3. Identification processes for (a) u=3% and (b) u=5%.

$$G(s) = \frac{39{,}2}{(1484{,}9s+1)(858{,}0s+1)} \tag{38}$$

$$G(s)=\frac{54{,}8}{(1523{,}6s+1)(209{,}7s+1)} \tag{39}$$

The control processes can be seen at Fig. 4. The starting values of system were used from (38), respectively (39). The ambient temperature was changing near 18°C with small air flow over the dryer. A sampling period T=5s was selected [12] after few time response tests.

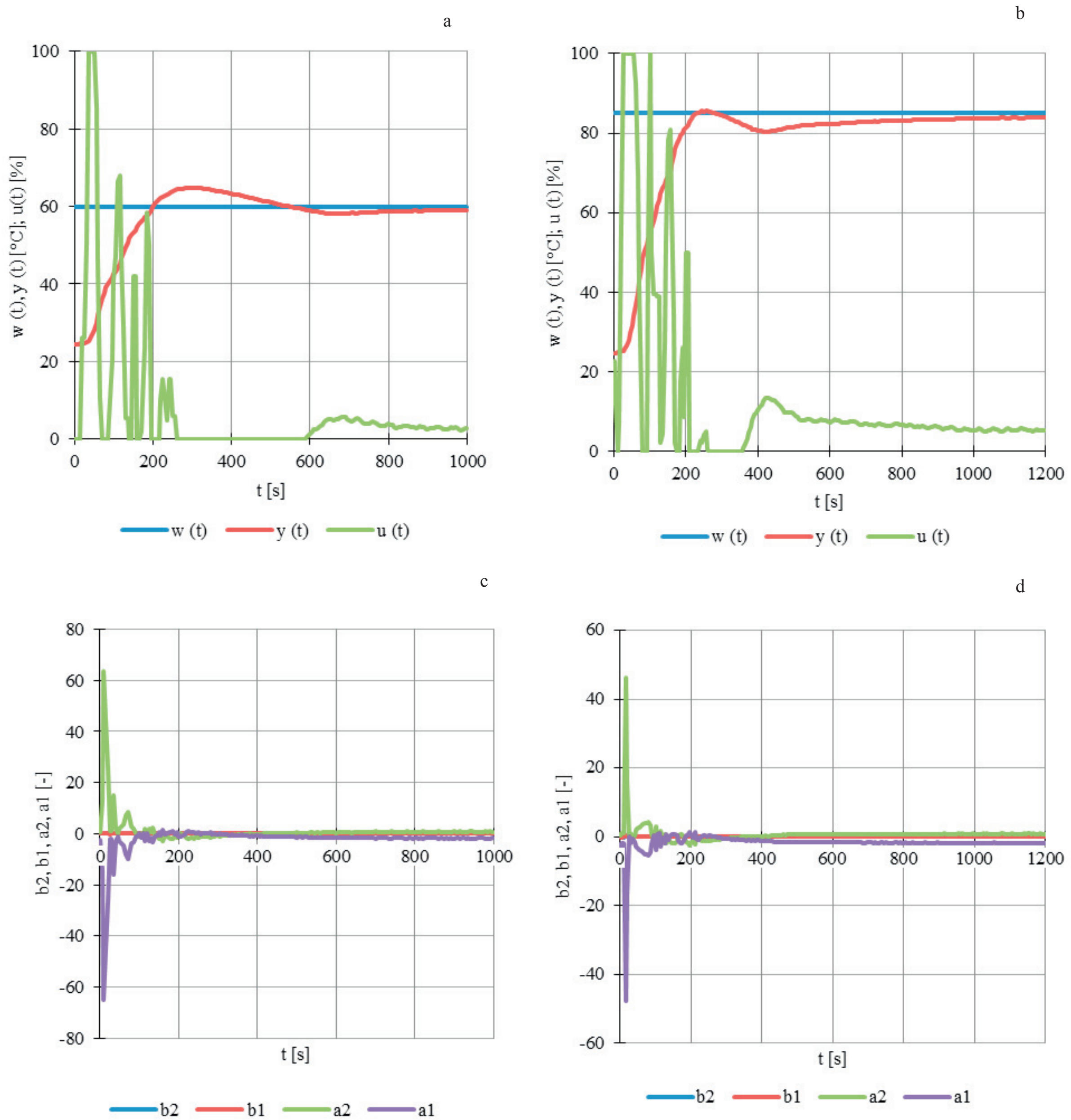

Fig. 4. The real control processes of drying printed circuit boards; (a) w=60°C; (b) w=85°C; (c) and (d) the corresponding system parameters during identification.

As can be seen on Fig. 4 (a), the control process achieved only 5% overshoot and next the temperature was stable. As is given in Fig. 4 (b), there was small undershoot for set value 85°C. It was probably caused by the identification process of system. Progression of each value of system is provided in Fig. 4 (c) and (d). Significant coefficients amplitudes and the controller output were probably caused by huge thermal hysteresis of the dryer.

Conclusion

In the article the implementation of the polynomial adaptive controller is described at the process of drying the printed circuit boards, because the requirement on the fast production of the PCBs with solder mask occurred. The solder mask needs the stable temperature during the drying process for the purpose of appropriate adhesion to the board. The high quality of temperature control is provided using this controller, which it leads to increase of the solder mask quality (the board on Fig. 2 were produced by the adaptive controller) and faster manufacturing. And also the implementation based on the 8-bit microcontroller proves that these microcontrollers still find applications in wide ranges of usage; and also it may refute that the 8-bit microcontrollers will be probably substituted by very fast 32-bit ARM microcontrollers, because theirs structure is further complicated and a price of substitution does not have to be adequate to new functions and expended effort.

The hardware design of the adaptive controller was conceptualized to universal usage in wide kinds of drying machines without redesign, because the adaptability automatically changes the controller parameters. However, in the future the algorithms might be adjusted for better response at the start of the control process and for elimination of small overshoots. Also in the future are planning controller extension with IPC/JEDEC standards [11] for reflow soldering, which can lead to elimination of other single-purpose devices.

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